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MINI-REVIEW: ECOLOGICAL SOLUTIONS TO GLOBAL FOOD SECURITY

Resilience and food security: rethinking an ecological concept

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Summary

1. Focusing on food production, in this paper we define resilience in the food security context as *maintaining production of sufficient and nutritious food in the face of chronic and acute environmental perturbations*. In agri-food systems, resilience is manifest over multiple spatial scales: field, farm, regional and global. Metrics comprise production and nutritional diversity as well as socio-economic stability of food supply.

2. Approaches to enhancing resilience show a progression from more ecologically based methods at small scales to more socially based interventions at larger scales. At the field scale, approaches include the use of mixtures of crop varieties, livestock breeds and forage species, polycultures and boosting ecosystem functions. Stress-tolerant crops, or with greater plasticity, provide technological solutions.

3. At the farm scale, resilience may be conferred by diversifying crops and livestock and by farmers implementing adaptive approaches in response to perturbations. Biodiverse landscapes may enhance resilience, but the evidence is weak. At regional to global scales, resilient food systems will be achieved by coordination and implementation of resilience approaches among farms, advice to farmers and targeted research.

4. *Synthesis*. Threats to food production are predicted to increase under climate change and land degradation. Holistic responses are needed that integrate across spatial scales. Ecological knowledge is critical, but should be implemented alongside agronomic solutions and socio-economic transformations.

Key-words: agro-ecology, diversity, food production, nutrition, perturbations, recovery, resistance, stability, transformation

Resilience is a multi-faceted concept for food security

The resilience concept has been developed in many disciplines, including ecology, engineering, agriculture and economics (Altieri *et al.* 2015; Martin & Sunley 2015; Oliver *et al.* 2015), with much cross-fertilisation of ideas. There is ongoing debate about precise definitions (Newton 2016). We do not aim to add to this debate, but to consider a pragmatic application of the resilience concept to food security. In ecology, resilience generally refers to the ability of an ecological system to resist a change in state or to recover in response to perturbations; but numerous state variables are used, including population size, community composition and ecological functions (Oliver *et al.* 2015). With regard to food security, resilience has been conceptualised in multiple ways, for example: (i) in terms of international development, by considering social structures and capacity building (Bene *et al.* 2016; Pelletier *et al.* 2016); (ii) by analysing sensitivity in models linking human population growth to food supply (Suweis *et al.* 2015); and (iii) maintaining agricultural production under climate change (Altieri *et al.* 2015).

In this mini-review, we explore this subject in terms of approaches for resilient food production in agricultural systems. We focus on multi-scale and multi-disciplinary issues to provide fresh view of how food production might become more resilient. Taking an agro-ecological perspective, we implement a working definition of resilience in terms of food security as: *maintaining production of sufficient and nutritious food in the face of chronic and acute environmental*

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perturbations. Following Oliver *et al.* (2015), a quantification of resilience would therefore represent the amount of time that food production is below a 'sufficient and nutritious' threshold, reflecting Target 2 of the Sustainable Development Goals. Our definition overlaps with that of *food system* resilience by Tendall *et al.* (2015): the capacity over time of a food system and its units at multiple levels, to provide sufficient, appropriate and accessible food to all, in the face of various and even unforeseen disturbances. While the definition of Tendall *et al.* (2015) includes aspects of demand – distribution, access and utilisation – we focus on the production side of food security. While related concepts such as stability, robustness and vulnerability can be studied individually (Urruty, Tailliez-Lefebvre & Huyghe 2016), they are subtly different metrics of dynamical systems, and resilience provides a pragmatic and overarching structure (Fig. 1). For example, instability of food supply can indicate low resilience (Suweis *et al.* 2015). Indeed, to apply generally to food security, resilience concepts must combine considerations of production responses to ongoing fluctuations in drivers, large perturbations or 'shocks' and long-term changes in these drivers (Fig. 1).

Food quantity, in terms of absolute amount of production or food calories, is the usual metric of food security and thus resilience. The need for varied and nutritious diets, to avoid both malnutrition and obesity, means nutritional diversity should also be factored into resilience considerations (Khoury *et al.* 2014; De Keersmaecker *et al.* 2016). Nutritional diversity and sufficient micronutrients are generally supplied through a varied diet, especially by including foodstuffs other than the cereal staples. Furthermore, relevant measures of resilience may also relate to economic and social aspects of food systems at multiple scales (Bene *et al.* 2016).

Resilience is manifest over multiple spatial scales in agri-food systems

In agri-food systems, resilience is manifest over multiple spatial scales. Most agro-ecologists focus on crop and livestock production at small, for example field, scales, but resilience of food production should also consider the farm, regional and global scales (Fig. 2).

To inform approaches for enhancing resilience, we summarise the major factors affecting food production. In-field crop yields vary primarily in response to climatic fluctuations, with temperature and water availability being the most common drivers (Ray *et al.* 2015). Other environmental drivers of both the quantity and quality of crop yields include pests and pathogens, and increasingly important chronic factors include rising salinity, deteriorating soils, new pests and decreasing pollinators (Lal 2009; Jaggard, Qi & Ober 2010; Potts *et al.* 2016). Similarly, climate, disease and poor forage quality are

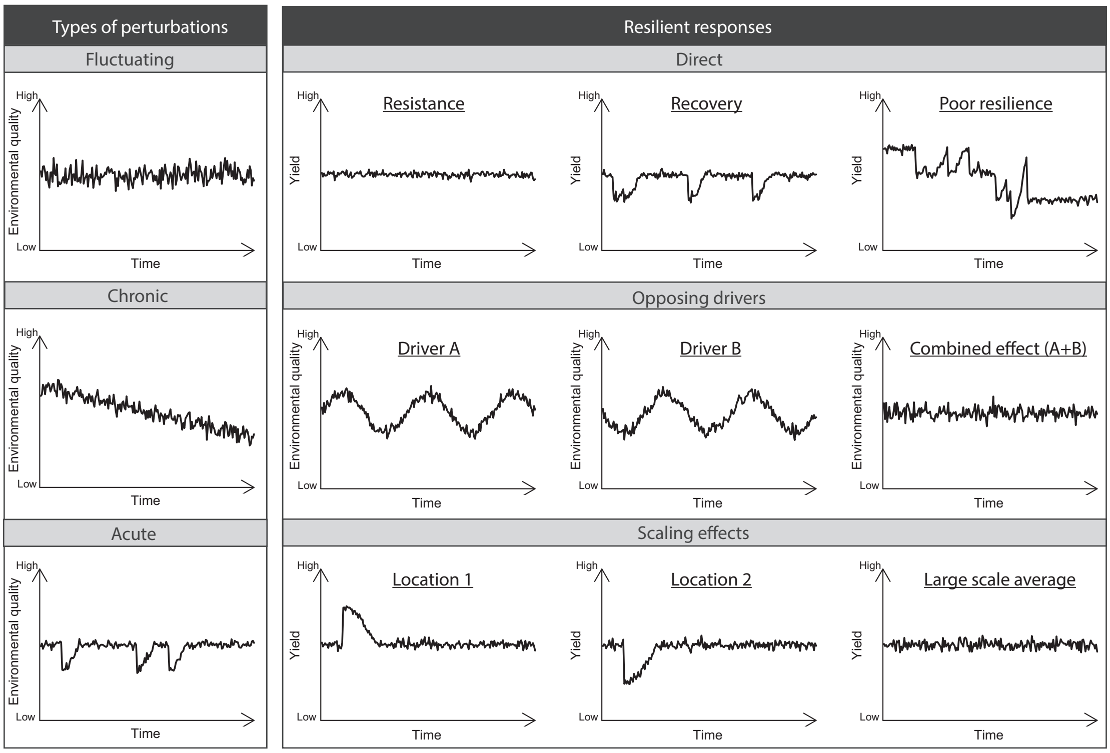

Fig. 1. Types of perturbation and forms of resilience in agri-food systems. Relevant perturbations comprise: ongoing fluctuations such as annual climatic variations; chronic perturbations, which are long term and potentially permanent changes in drivers, such as rising average temperature; and acute, that is short-term, perturbations such as extreme weather events. Resilience (e.g. in yield) can be achieved through resisting or recovering from perturbations, in contrast to large, and sometimes enduring, losses in production. In addition, because food production is affected by multiple drivers, resilience may be delivered by opposing patterns in these drivers. Finally, while perturbations may affect production at a local scale, losses in some locations may be countered by enhanced yield at other locations, leading to resilience at larger scales.

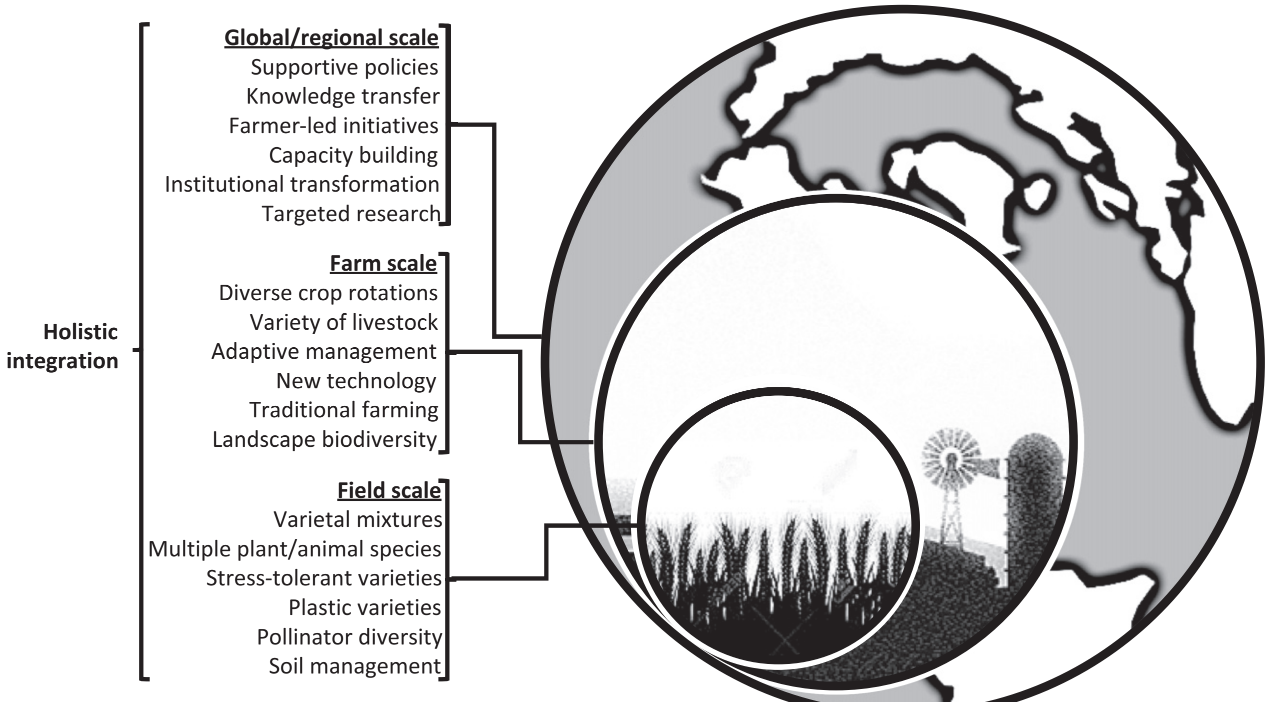

Fig. 2. Resilience in the production of sufficient and nutritious food is manifest at multiple scales. This conceptual diagram illustrates three broad scales and the multi-faceted approaches to conferring resilience discussed in the paper, which progress from more ecologically based methods at smaller scales to more socially based interventions at larger scales. A holistic approach to resilience involves working across these scales and combining ecological and social interventions.

among the environmental factors that affect production in livestock systems (Nardone *et al.* 2010).

At larger spatial scales, these environmental drivers remain important, with their overall impact depending on their spatial and temporal patterns; for example el Niño has synchronous impacts on crop yields over large areas (Iizumi *et al.* 2014). But, from the farm to global scales, socio-economic perturbations become important. Considering the supply-side of food security, these include changes in food needs, price volatilities for inputs, policy decisions and scarcities in land, labour, finances and machinery (Rodriguez *et al.* 2011; Golub *et al.* 2013). For example, globalisation and urbanisation are suggested to have increased homogeneity of food supplies globally, with consequences for nutrition (Khoury *et al.* 2014).

Resilience at these different scales is not necessarily nested, meaning food security may not always require resilience at small scales; for example poor production in a field, farm or region may be balanced by increased production elsewhere (Fig. 1), so that there is resilience at larger scales (Reidsma *et al.* 2010). Furthermore, because food production has multiple drivers, some degree of resilience may arise through asynchrony or conflicts among these drivers (Fig. 1). For example, adverse weather which decreases crop growth may also limit pests (Caffarra *et al.* 2012). These multiple scales and the interacting forms of perturbation mean that approaches to improve resilience of food production should be multi-faceted. These approaches need to take account of both acute and chronic perturbations; for example while production in 1 year may be greatly decreased due to an extreme weather event but recover the following year, chronic soil degradation may cause ongoing declines in production (Fig. 1). Complementary approaches to enhancing resilience should be considered at different scales, and we describe a progression from more ecologically based interventions at small scales to more socially based approaches at larger scales (Fig. 2).

Approaches to enhancing resilience

At the field scale, ecologically inspired approaches invoke the role of diversity at some taxonomic level, which is hypothesised to impart resilience through different taxa having complementary responses to perturbations. Thus, varietal mixtures of a crop can achieve greater yield resilience than mono-varietal plantings (Creissen, Jorgensen & Brown 2016). Yield shows greater resilience to climatic perturbations in more species-rich or more genetically diverse forage systems (Prieto *et al.* 2015), and it is suggested that stocking multiple livestock species might also enhance resilience (Duru & Therond 2015). While there is little evidence for such benefits from planting multiple crop species in polycultures (Thiessen Martens, Entz & Wonneck 2015), increased diversity of crop types in a rotation can enhance yield resilience (Gaudin *et al.* 2015). Biotechnological approaches involve breeding crop and forage varieties that are less affected by perturbations, through being more resistant to a specific driver, such as drought (Birthal *et al.* 2015; Kissoudis *et al.* 2016), or having greater plasticity (Bloomfield, Rose & King 2014). Some crops, such as maize, exhibit local adaptation to more extreme climates (Butler & Huybers 2013), which provides a similar resource. A final set of approaches considers the agroecosystem more broadly, enhancing resilience of production by bolstering the resilience of key functions. Examples are: improving soil condition, such as by agroforestry or adding organic matter (Rivest *et al.* 2013; Zhang *et al.* 2016); or by maintaining wild bee diversity to provide a resilient pollination service (Potts *et al.* 2016).

At the farm scale, more diverse crop rotations can aid yield resilience (Davis *et al.* 2012). More generally, adaptive responses by the farmer to perturbations provide an integrated way to manage for resilience (Reidsma *et al.* 2010; Rodriguez *et al.* 2011). This involves flexibility in crop, forage or livestock selection and husbandry and implementing new technologies in response to changing conditions. For example, Birthal *et al.* (2015) suggested that rice yields in India are becoming resilient to increased drought frequency through farmers selecting appropriate varieties, expanding irrigation and utilising technologies such as micro-irrigation. Some aspects of traditional farming may confer resilience, such as the raised bed cultivation systems used in Latin American seasonally flooded savannas (Altieri *et al.* 2015). But reinstating traditional farming should not be seen as a panacea as such systems do not necessarily have higher resilience (De Keersmaecker *et al.* 2016), and it is likely they are poorly equipped to cope with climate and other environmental changes. Similarly, while it is hypothesised that biodiverse landscapes in and around farms enhance agroecosystem resilience (Tscharntke *et al.* 2005), there is little evidence.

At regional to global scales, approaches to resilient food production should ensure the approaches detailed for field to farm scales are implemented widely in a coordinated fashion. While policies across the world have tended to erode farm system resilience (Anderies, Ryan & Walker 2006), new policies such as the EU's crop diversification measure could be beneficial (Mahy *et al.* 2015). Knowledge transfer to and among farmers, building capacity and enhancing social networks may be more effective approaches, allowing farmers to self-organise to address resilience issues in an adaptive fashion (Carlisle 2014; Pelletier *et al.* 2016), and this can be addressed by policies (Anderies *et al.* 2013). Many national and international institutional structures have complex and interacting consequences for food production resilience, through impacts on resources, costs and collective actions; and there is a need for these institutions to adapt and transform to new types of perturbation (Anderies *et al.* 2013). Ecological and agronomic research institutions can help, for example by developing new crop types (Kissoudis *et al.* 2016) and elucidating links between biodiversity and agroecosystem resilience (Oliver *et al.* 2015).

Enhancing resilience in terms of food security requires holistic, multi-scale actions

Threats to food security and the resilience of agri-food systems are predicted to increase under climate change and ongoing land degradation. Ecological principles inform responses to enhance the resilience of agricultural production at field and farm scales, generally through diversity-resilience relationships. One challenge for ecologists is to provide better evidence for such relationships; for example whether landscape-scale biodiversity confers agroecosystem resilience. Ecologists might also work with plant breeders in developing crops and varieties showing complementary response to perturbations and in designing resilient mixtures and rotations. The approaches to resilience that we detail mostly concern agricultural production as there is little relevant research on nutritional diversity. This is a clear knowledge gap and, for example, Haddad *et al.* (2016) called for research into yield resilience of neglected nutritious fruits and vegetables. Ultimately, there is a need to merge ecological approaches into a holistic interpretation of resilience that considers both production and nutritional diversity at multiple scales, with socially based approaches from the farm up to the global food system. In this way, ecologists can be active in the design of adaptive agri-food systems based on socio-ecological evidence that can help in enhancing resilience of food security.

Authors' contributions

J.M.B. conceived the idea and led the writing of the manuscript; K.L.D.A., A.M., T.H.O., L.C.T., A.P.W. and R.F.P. contributed critically to the concepts and to the drafts. All authors gave final approval for publication.

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Data accessibility

This paper did not use data.

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